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Office of Nonproliferation Research and Development

SNM Movement Detection / Radiation Sensors and Advanced Materials Portfolio Review

Correcting the Non-Uniformity in the Gamma-Ray Response of Large-Area CZT

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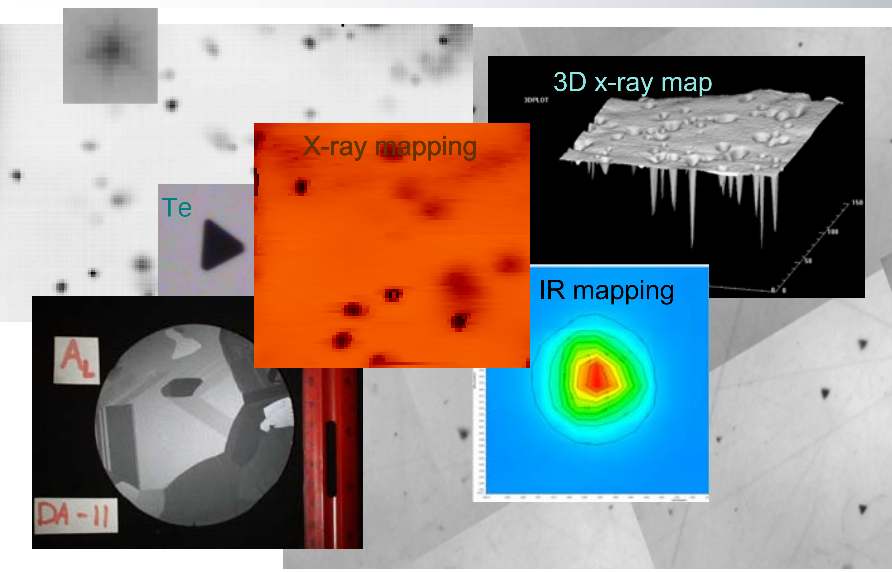
Research Team



Project started January 2006

Budget: FY06 - $400K
FY07 - $540K
FY08 - $565K + $125K*
*Equipment budget

Budget Spent/Committed: $353,243

Budget Remaining: $212,757

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University sub-contractors: A. Burger, Fisk University and Y. C. Chang, University of Illinois.

Industrial collaborators: H. Chen, Redlen, Vancouver, BC, Canada; C. Szeles, eV Products, Saxonburg, PA; L. Li, Yinnel Tech, South Bend, IN; K. Mandel, EIC Labs, Boston, MA.

Other Universities: Fisk University (3), University of Michigan, Cornell University, Tennessee Technological University, Idaho State University, Chernivtsi National University, Vanderbilt University, and University of Freiburg.

Project Objectives and Long-Term Goal

1) Determine for the first time the properties limiting the performance of CZT detectors

2) Develop efficient, non-destructive techniques to measure the quality of detector materials

3) Provide rapid feedback to crystal growers and, in conjunction with suppliers, improve CZT detector performance as measured by device energy resolution, efficiency, stability and cost

Goal: Stable commercial supply of low-cost, high energy resolution (0.5% FWHM at 662 keV) CZT crystals for detecting, characterizing and imaging nuclear and radiological materials in a wide variety of field conditions

Background

CZT is best candidate material today for room-temperature, solid-state nuclear radiation detectors. Broad applicability of CZT for nuclear nonproliferation applications is limited by three material problems.

(1) Poor hole collection

(2) Electron trapping by point defects

Known problems.
Both electron and hole trapping can be corrected for uniform CZT detectors.

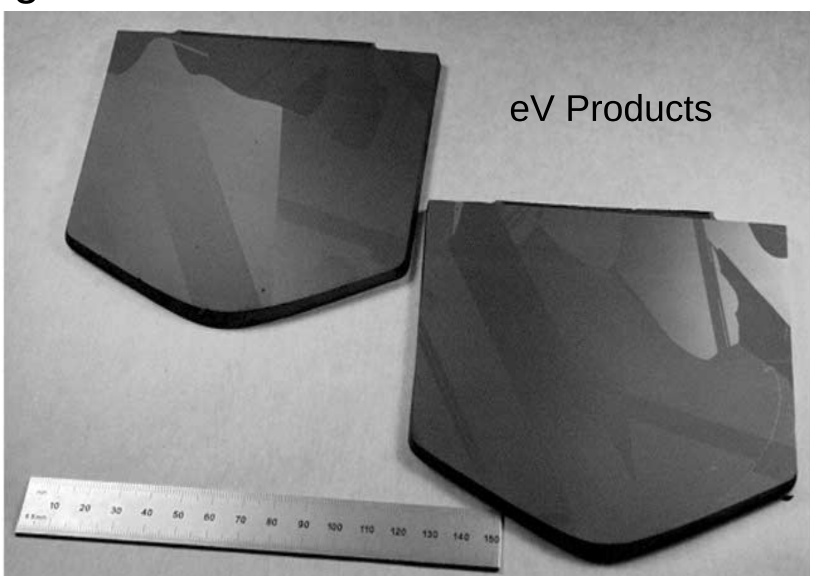
(3) Non-uniformity of single-crystal CZT

The importance of this problem was not recognized until large-volume single-crystal CZT became available. No effective electronic solution exists.

Approach: Understand and overcome the problem of non-uniformity in large-volume CZT detectors

BNL has developed unique tools to map the charge-collection uniformity in semiconductor detectors. Crystals are provided by Redlen, eV Products, Yinnel Tech, EIC, Orbotech, Eurorad, CIEMAT, IMEM-CNR, Institute of Solid-State Physics, and Univ. of Freiburg.

Example of a CZT wafer with multiple grain boundaries and twins.



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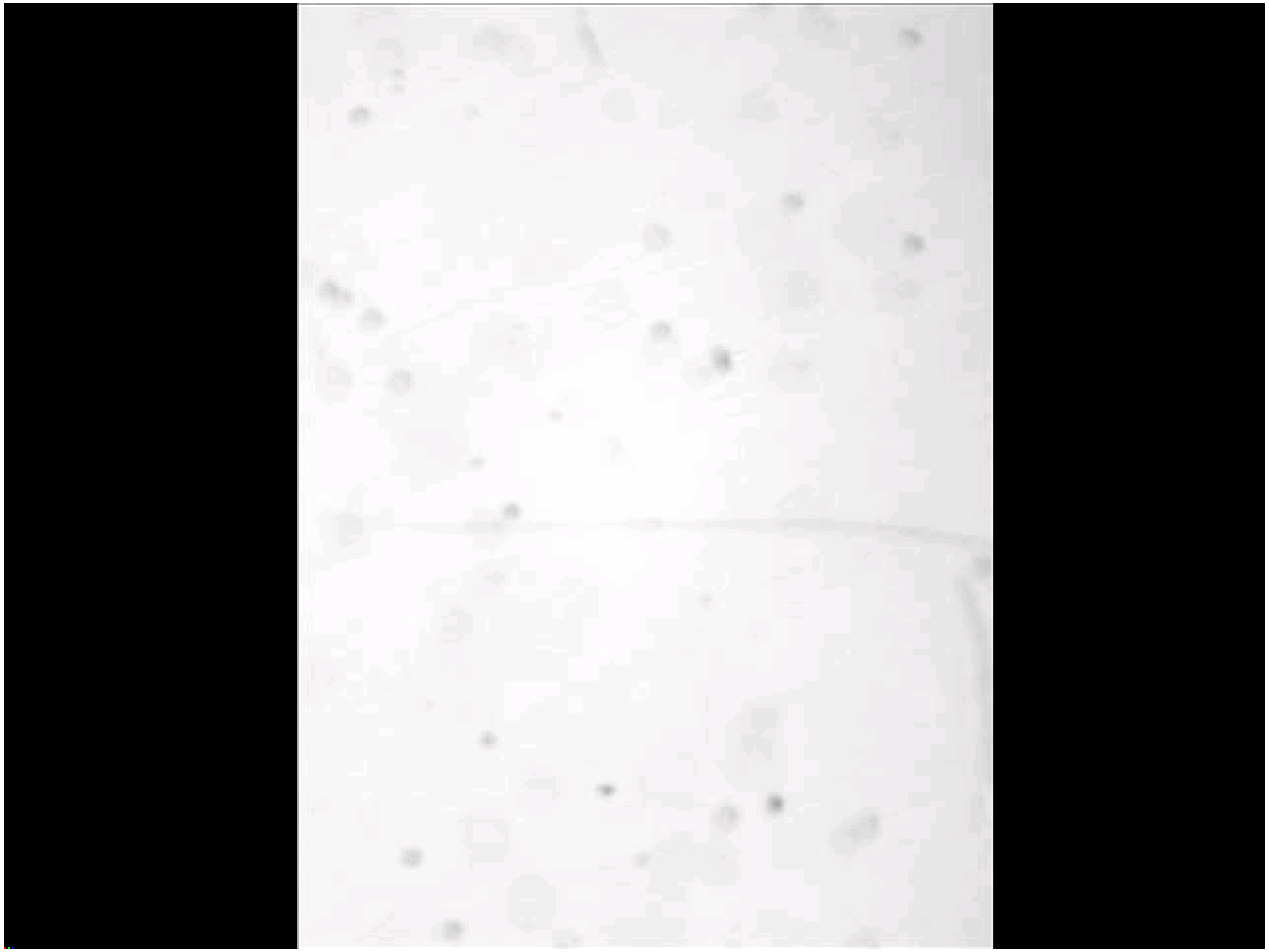
Today single crystals up to 300 cm^3 are available. But the device size is still limited to ~1-2 cm^3. Attempts to use bigger crystals typically result in medium-to-low energy resolution.

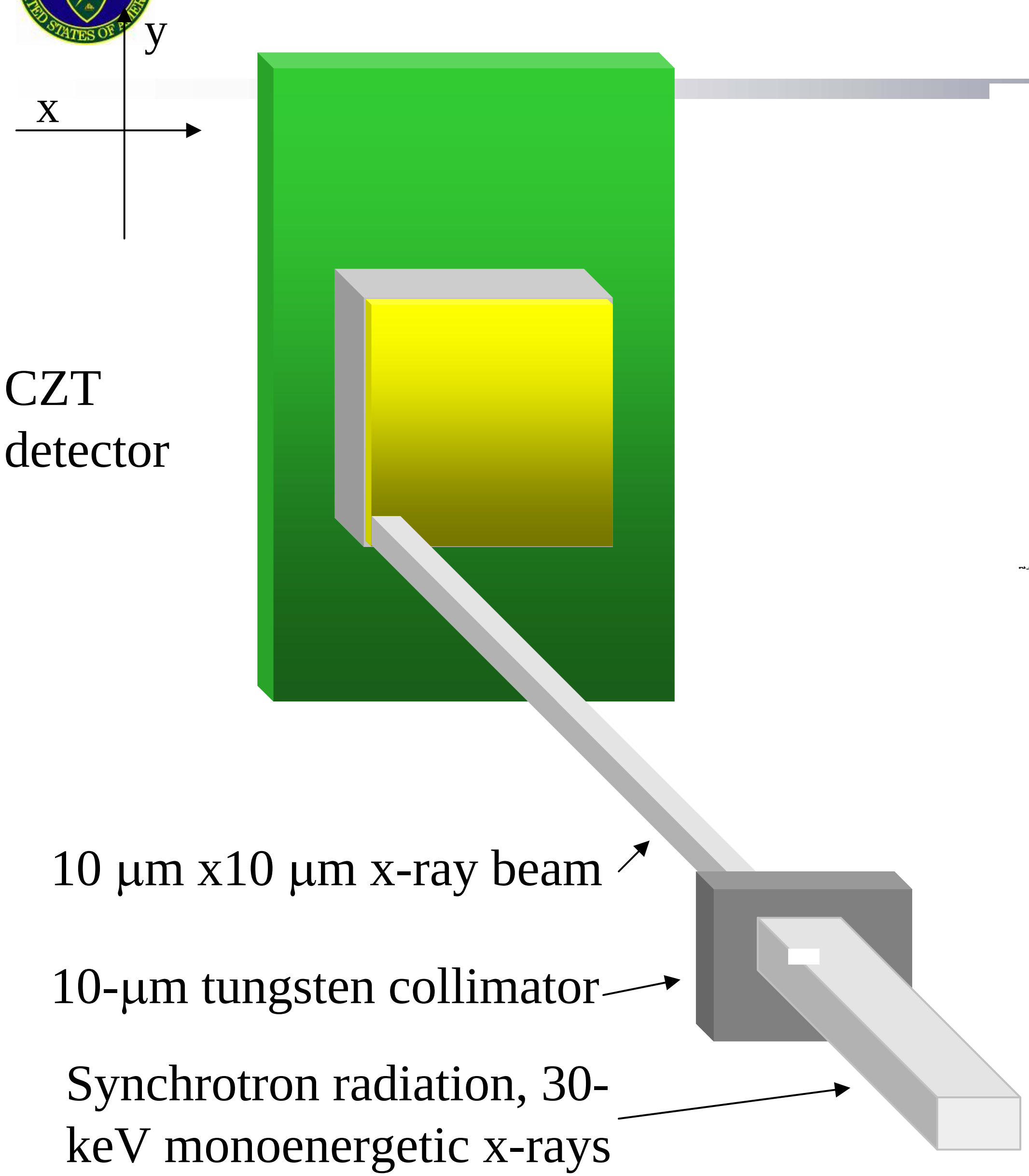
For a long time this was a mystery – one that BNL was able to solve by using high-intensity X-ray beams at the National Synchrotron Light Source.

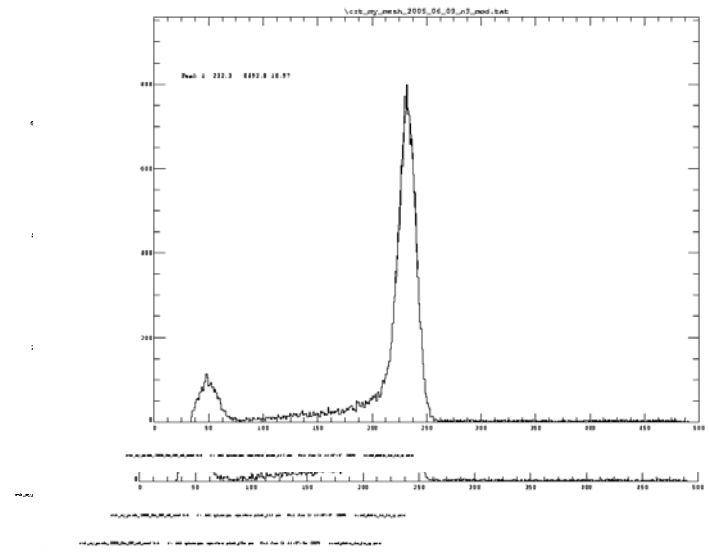
Automated infrared mapping system assembled to quantify Te inclusions for different growth runs



- ➢Scans in the z (depth) direction with ~100um steps
- ➢Algorithm applied that accurately records the size and number of the Te inclusions in different layers
- ➢ Good agreement with manual counting method

Micro-scale detector mapping measurement

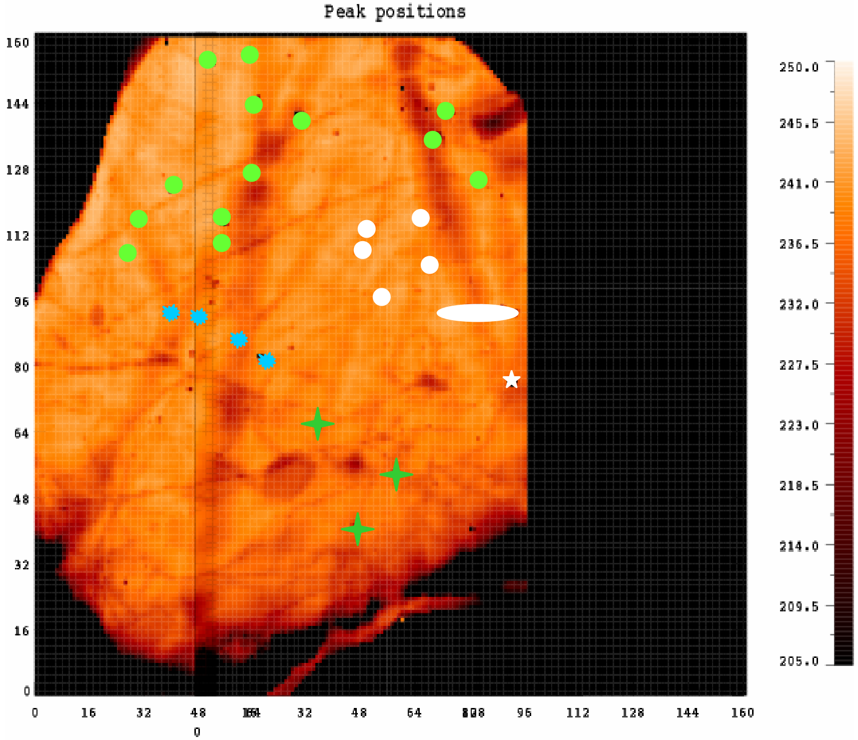




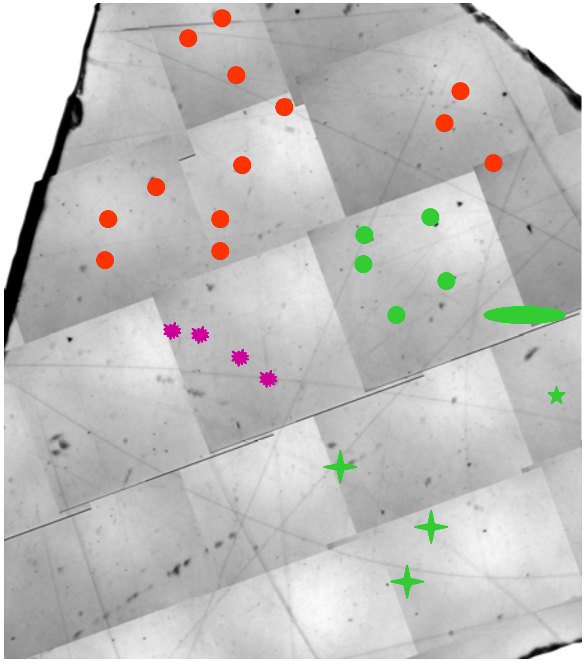
Using a MCA we record the energy spectrum for each point of the scanned detector area.
Then we plot the peak channel vs. position.

Correlations between x-ray map & IR image

This x-ray map shows the degraded regions precisely correspond to Te inclusions on the right

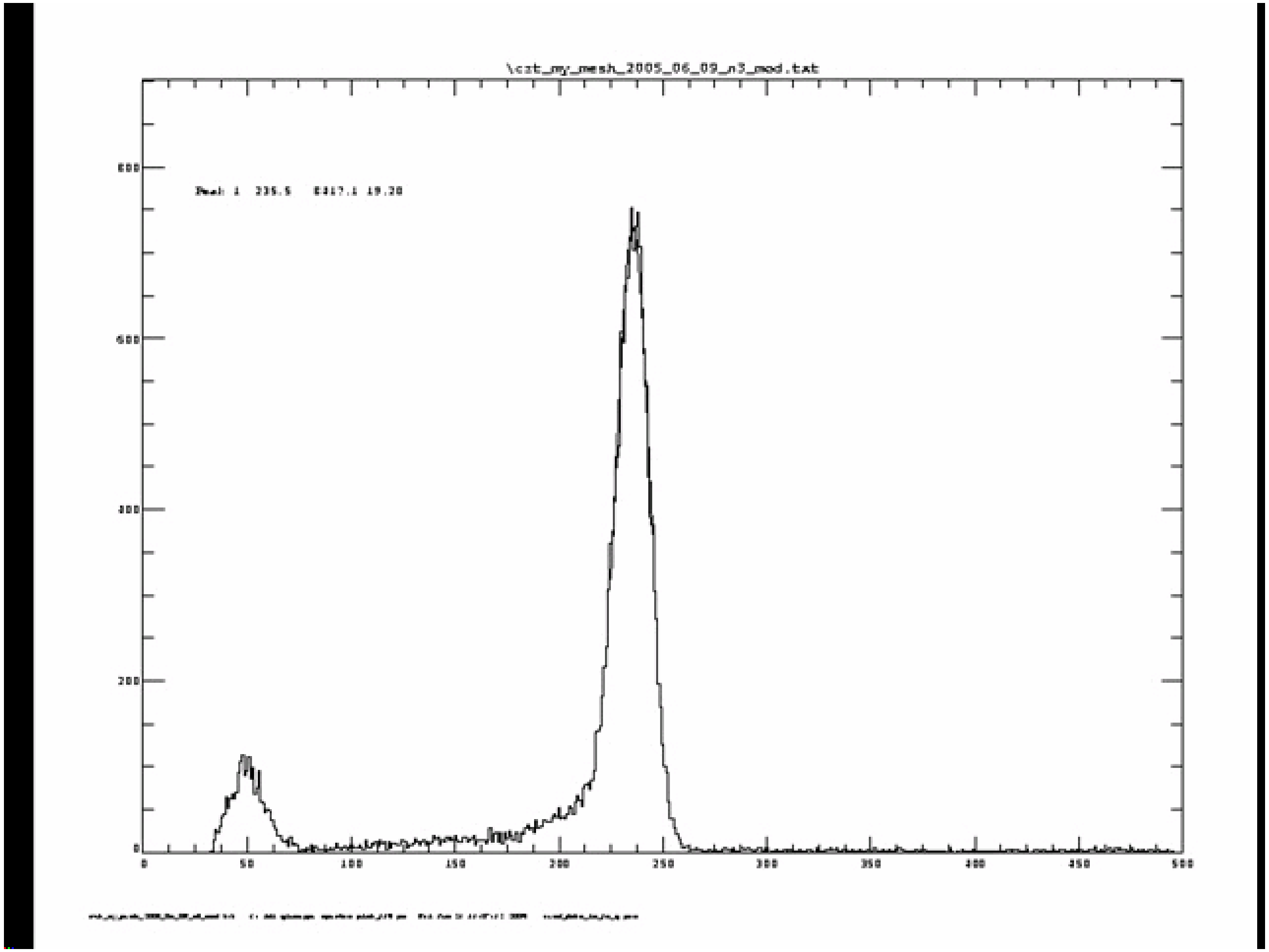


This IR image shows Te inclusions, which could be identified by composition and shape



Very high correlation found for all CZT samples.

Response map near a Te inclusion



100 µm x 100 µm area
10-µm x 10-µm pinhole
5-µm step size

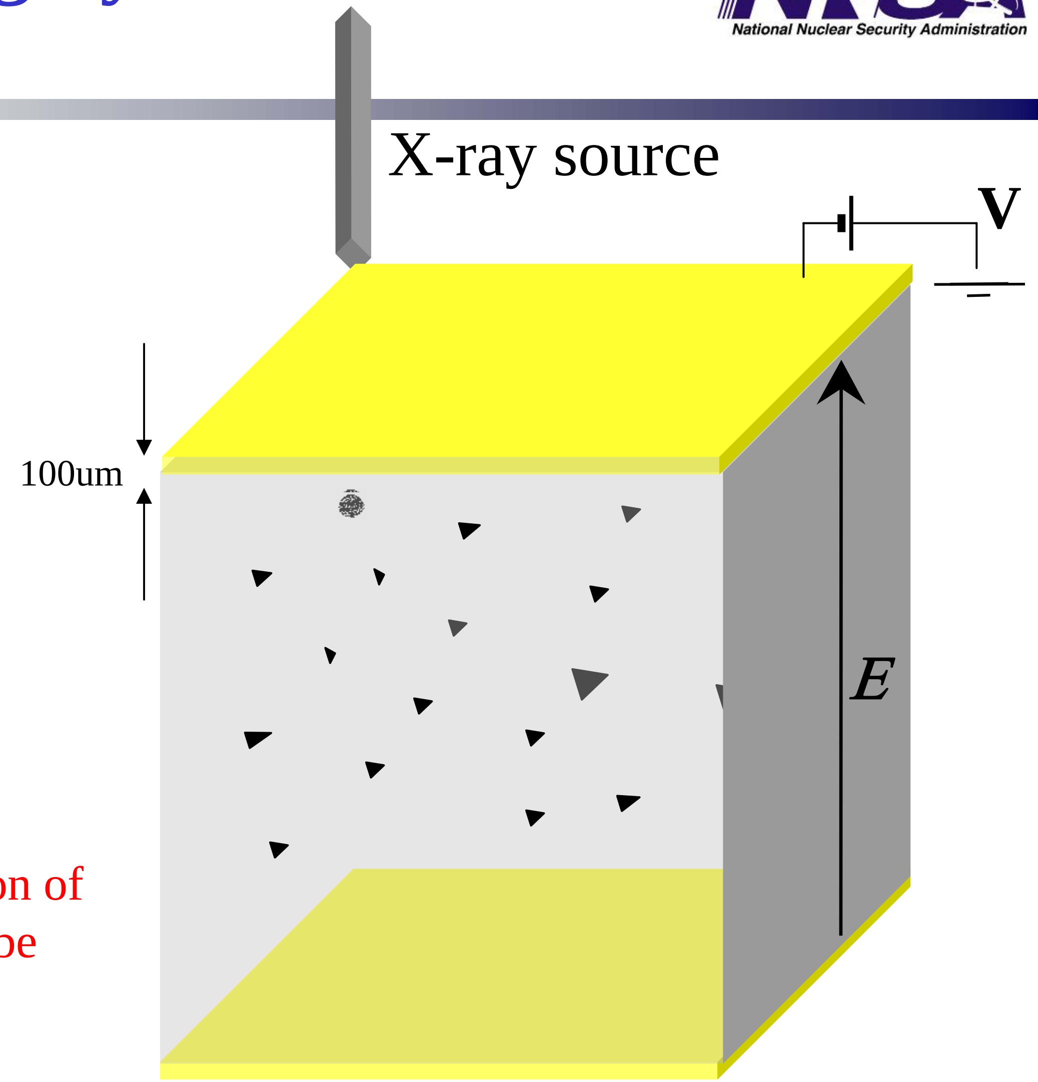
Electron trapping by Te inclusions

Assuming no other defects (such as cracks, grain boundaries, and twins) are present.

Charge trapped by an individual inclusion:

$$Q = Q_i\left(1-\eta_i\left[1-\exp\left(-\frac{D_i}{E_i\mu_i\tau_i}\right)\right]\right)$$

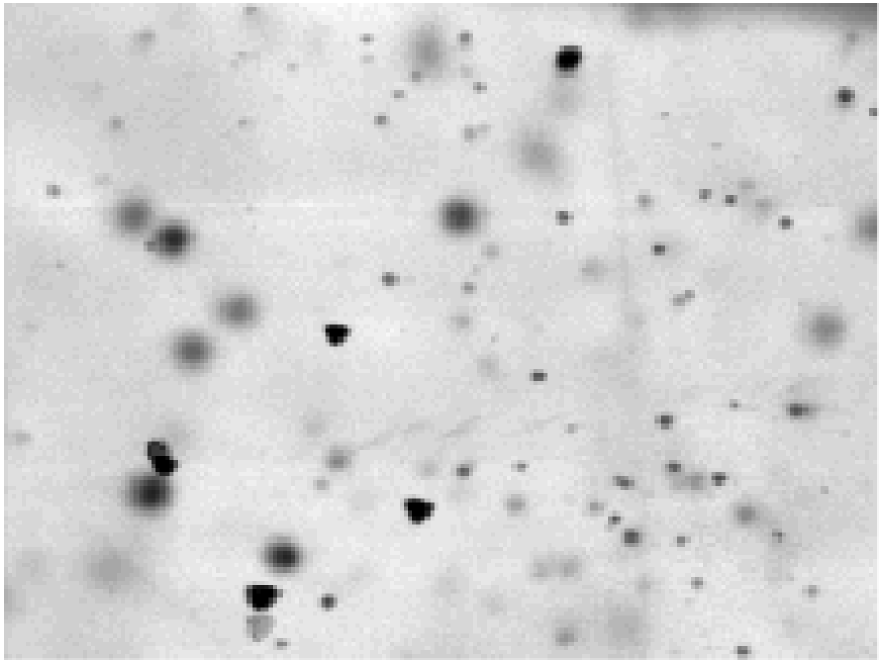
Many electrons are trapped per interaction. Stochastic process due to random distribution of Te inclusions => these fluctuations cannot be corrected!



CZT detector

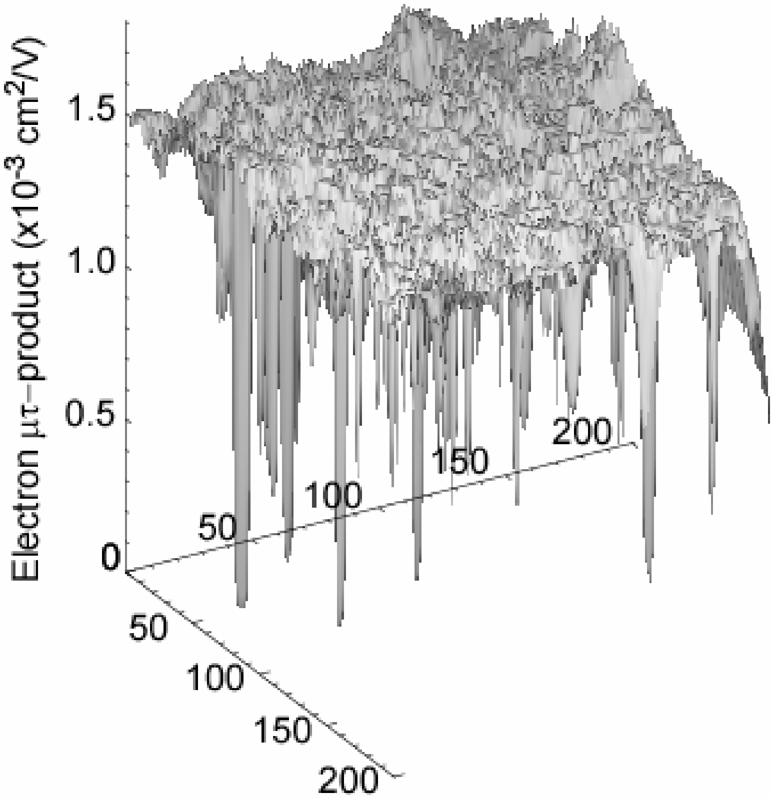
Micro-scale variations in the electron mu-tau-product observed

Charge-collection efficiency map

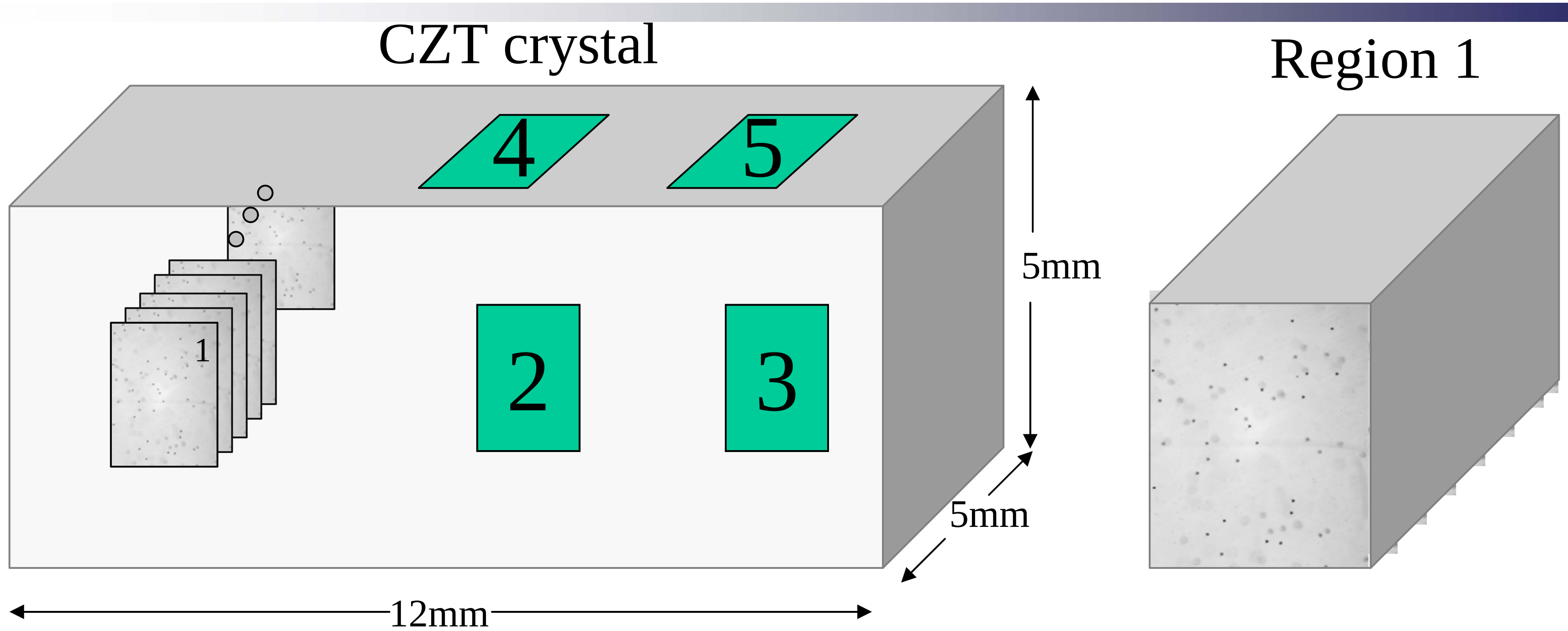


2x1.5 mm^2 area
1.5-mm thick
Spot size 10x10 μm^2

$\mu\tau$ map



Measurements of concentration, distribution and size of Te inclusions



1. We count the # of Te inclusions (the algorithm rejects those out of focus) in each image
2. We calculate the concentration of Te inclusions in each volumetric region
3. We average over these 5 regions to calculate the concentration of Te inclusions per cm^3

Results:

Concentration of Te inclusions per cm^3

Distribution and sizes

3-D mapping of Te inclusions

Reconstructed region: 1x1x5 mm^3

Te inclusions represented by dark discs. Discs diameters equal to 5x (a) and 25x (b) of actual diameters of inclusions.

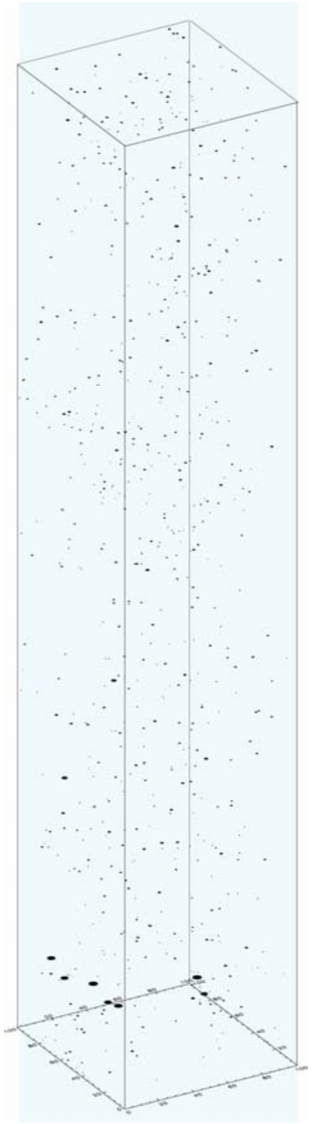
Inclusions often concentrate along the lines.

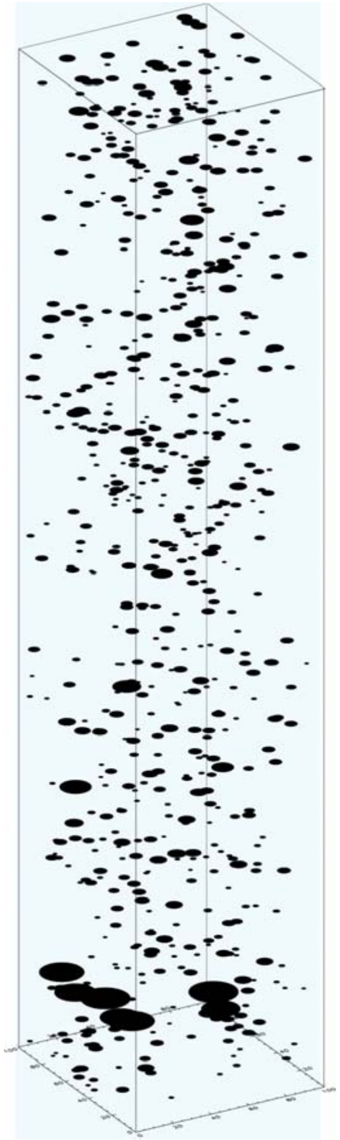
Typical concentration is 10^4 - 10^6 cm^{-3}.

Typical excess of Te is 0.01 – 0.03 atomic %.

Total geometrical area is about 0.07 cm^2 per cm-thickness.

(a)



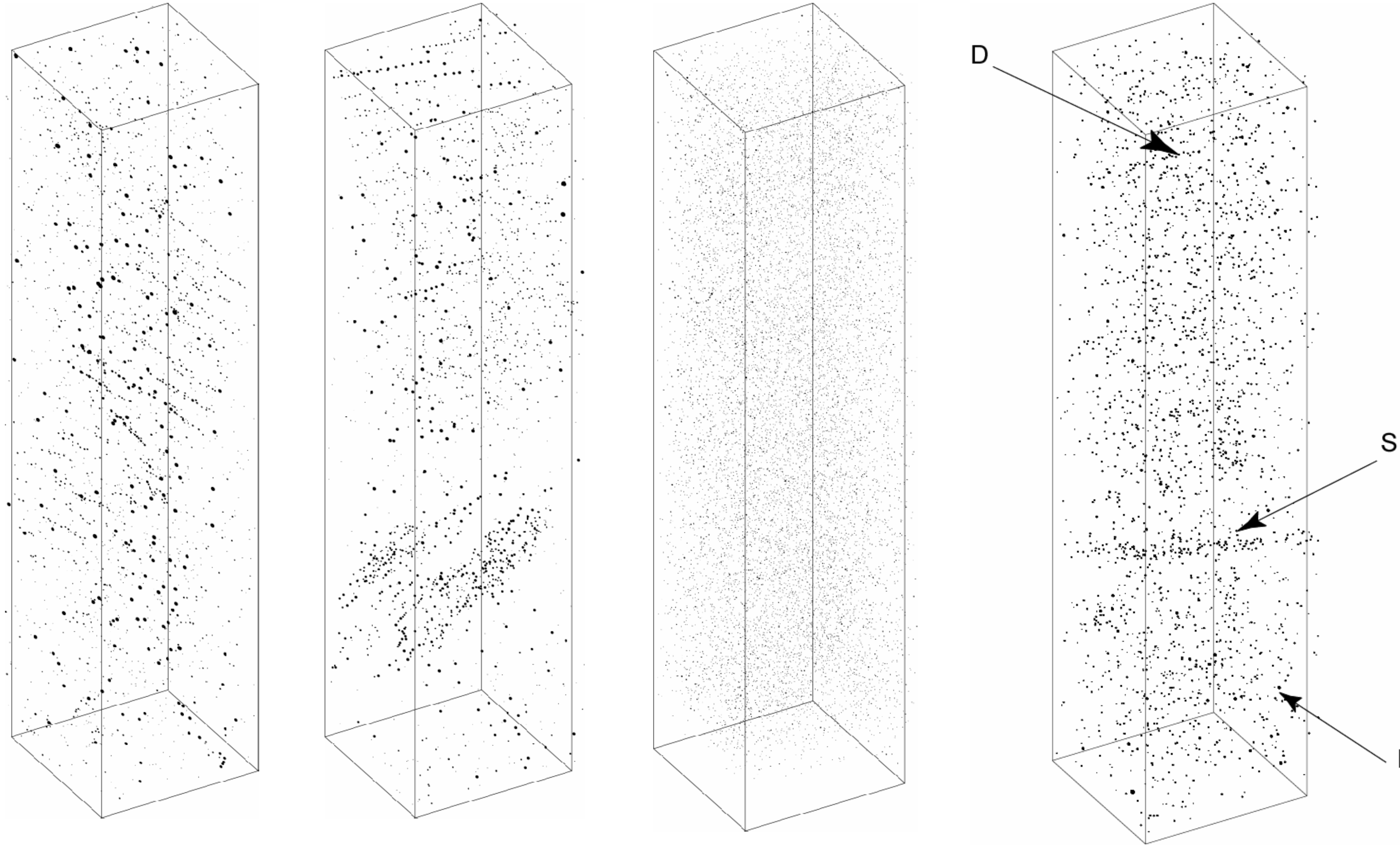


(b)

Locations of the inclusions reconstructed using ~50 sequential images taken in the Z-direction

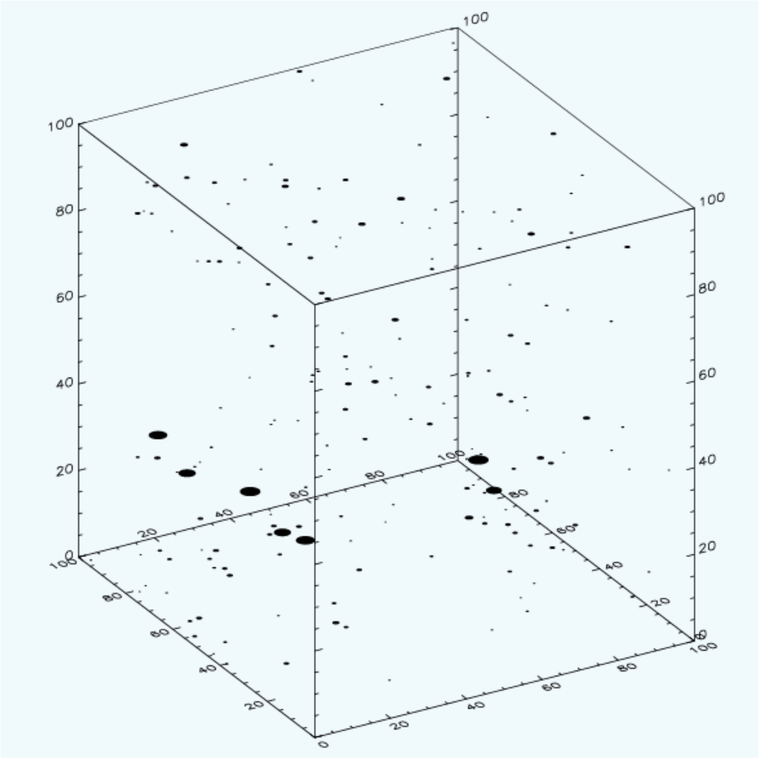
Reconstructed 3D distributions of Te secondary phases for different samples

CZT volume: 1x1.5x5 mm^3



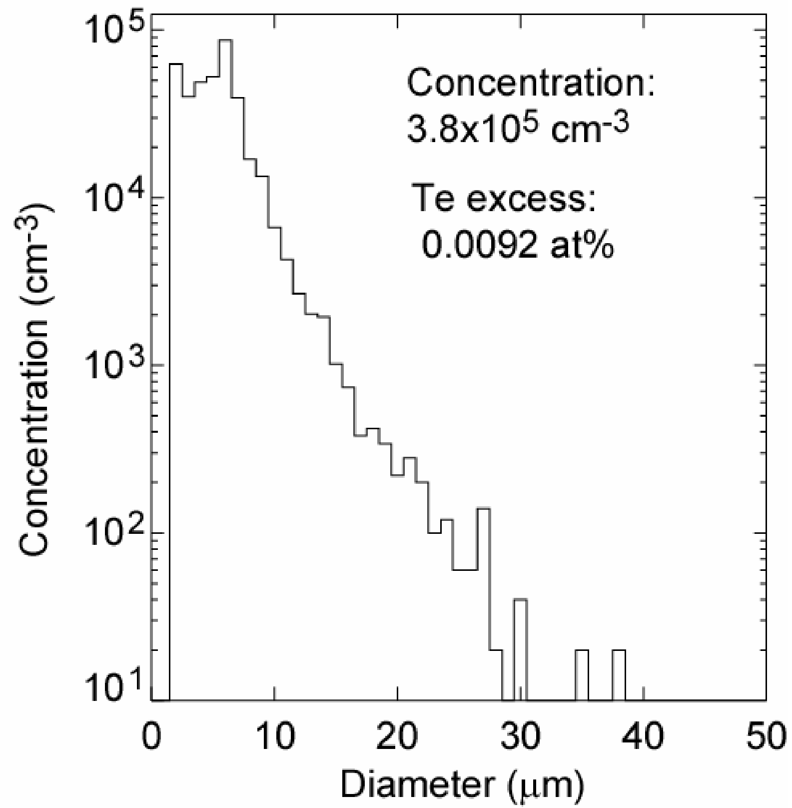
Distributions of Te inclusions quantified

Te inclusions represented by dark discs (5x of actual diameters)



1x1x1 mm^3

Size distribution of Te inclusions



Measured vs. simulated X-ray maps

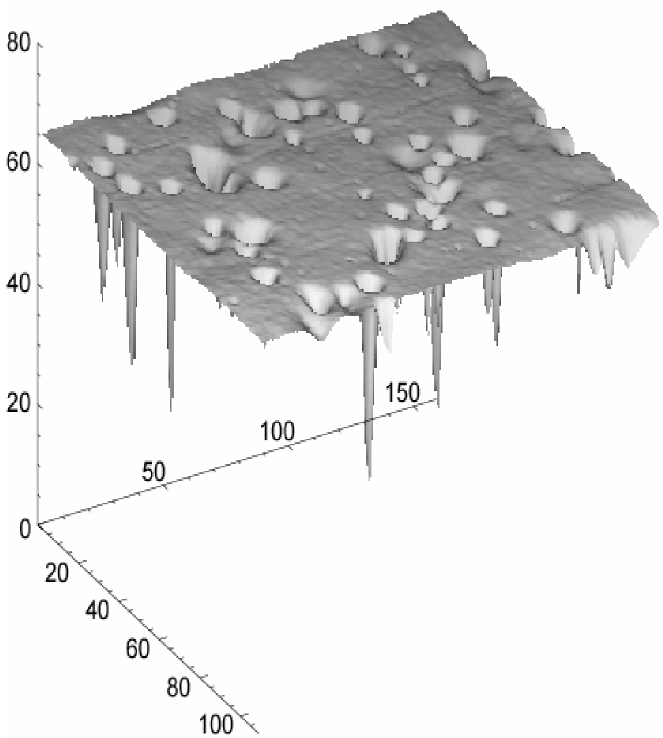
1-mm thick CZT sample

Energy 30 keV; beam size 10x10 um^2

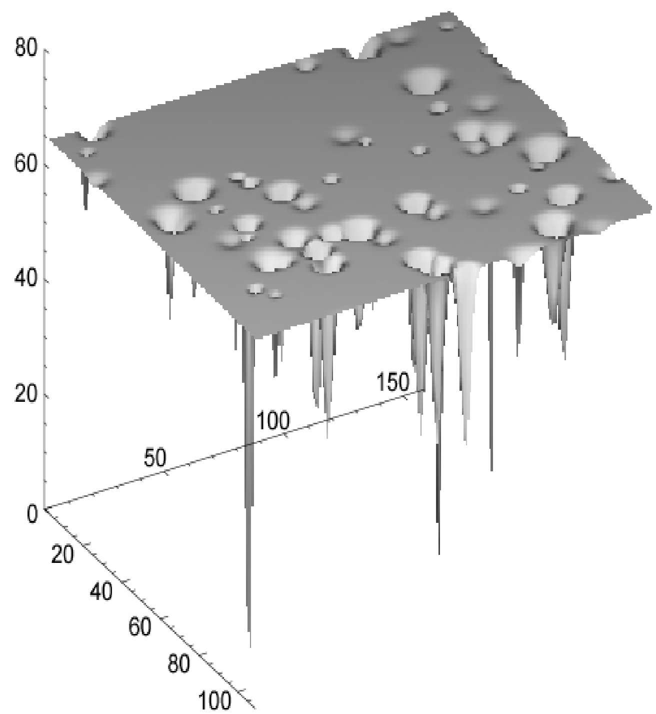
Inclusions size 1-20 um

Total concentration ~10^5 cm^{-3}

Measured

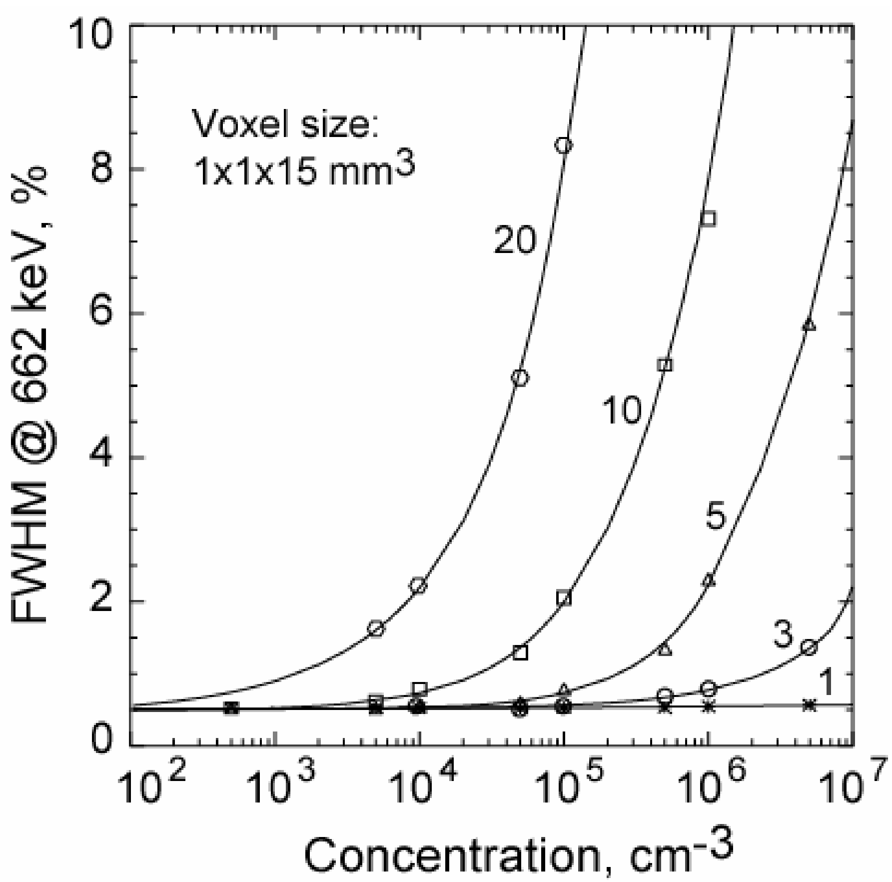


Simulated



This comparison suggests that the effective and actual sizes of Te inclusions are close.

Photo-peak broadening due to electron trapping caused by Te inclusions



FWHM (% @ 662 keV) of photo-peak vs. size (1-20 μm diameter) and concentration (up to $5x10^6$ cm^{-3}) of Te inclusions.

The plots are calculated for a 1x1x15 mm^3 voxel of an ideal single-carrier device irradiated with a ^{137}Cs source.

Electric field is 2000 V/cm.

Simulations predict that Te inclusions with sizes of < 2 μm can be tolerated. They behave as ordinary traps.

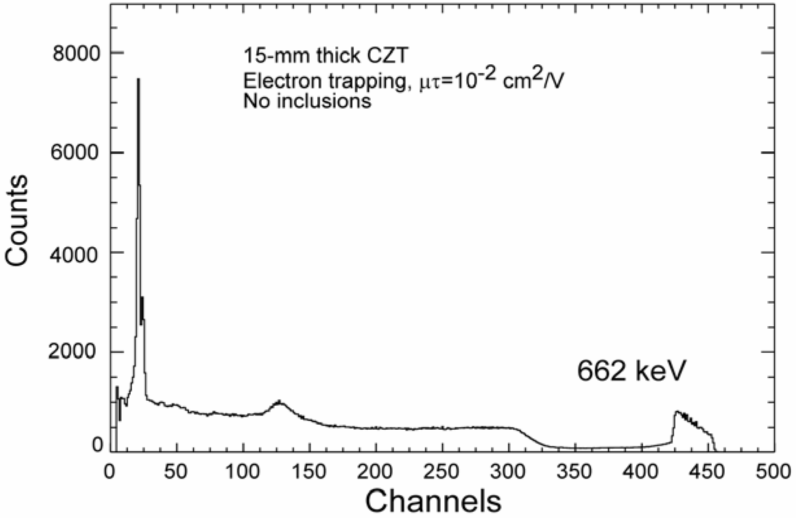
These results were confirmed from actual measurements!

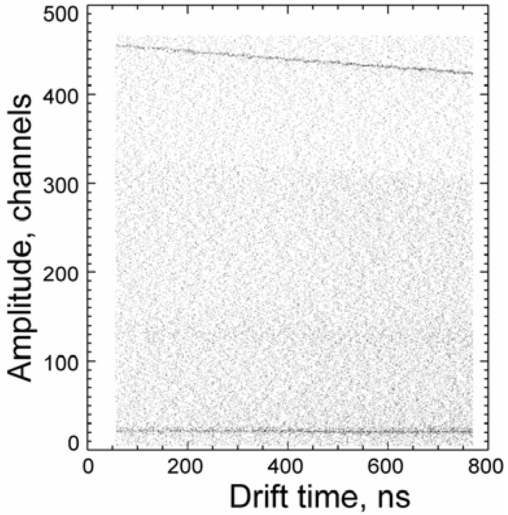
First high-resolution maps of hole mu-tau product

Hole charge-collection map

31keV; -170V
Spot size: 25um;

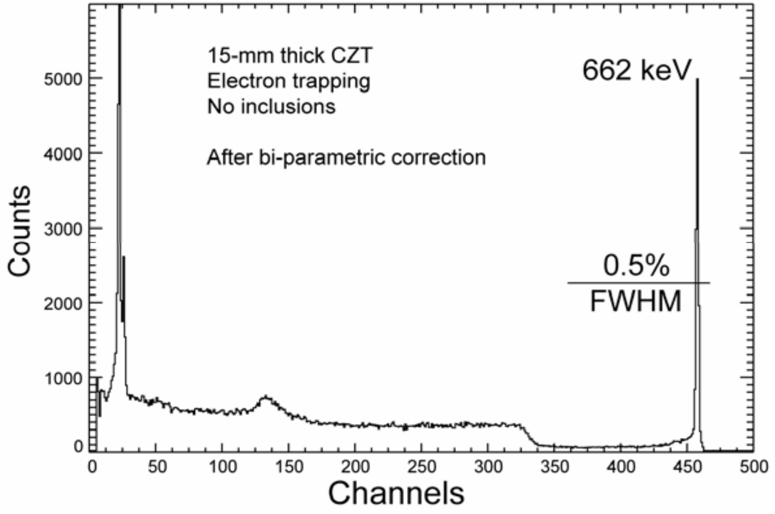
Conventional electron trapping (no Te inclusions) in a 15-mm thick device

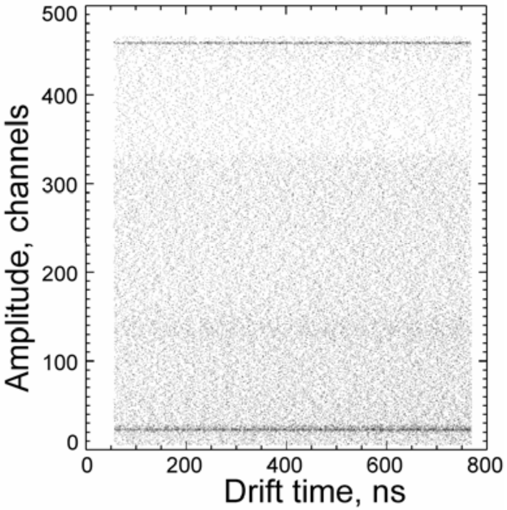




Pulse-height spectrum simulated for a 1x1x15 mm^3 voxel of the ideal single-carrier detector.

The $\mu\tau$-product is 10^{-2} cm^2/V.





Electron trapping can be easily corrected!

Hypothesis: *Te secondary phases are caused by Te inclusions*

Two Definitions:

- **The term "inclusion" describes any volume of material trapped inside a crystal during its formation.**

- **The term "Te precipitate" describes the coalescence of cadmium vacancies due to the limited solid solubility of Te in CZT.**

Results point to new directions/thrusts for CZT growth and post-growth processing

Goal: Reduce the size and concentration of Te inclusions in CZT crystals without adversely affecting the electrical resistivity or mobility-lifetime product for electrons

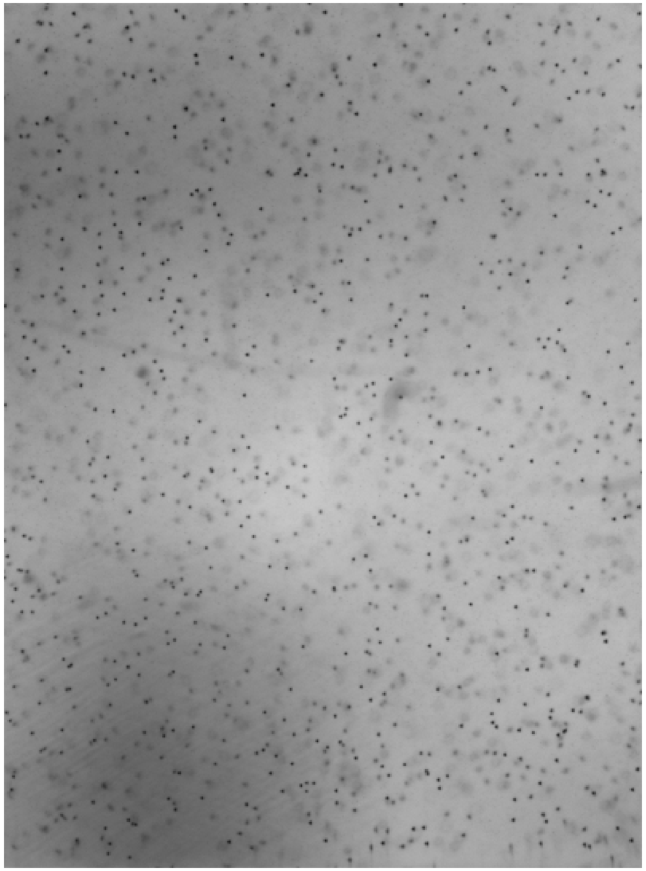
Approach: Perform new growth experiments and couple with mapping of device non-uniformity and presence of Te-rich inclusions

- Better mixing of the melt by rotation, magnetic stirring, or other means
- Modify ampoule design
- Reduce amount of excess Te in source materials
- Lower growth temperatures to reduce Cd loss
- Reduce Cd loss during growth and cool-down, including use of closed systems or gas over-pressures
- Post-growth thermal annealing in Cd (or Zn) vapors
- In-situ time-resolved measurements of conductivity and Te-inclusion size and distribution under controlled heating and cooling rates

Large reductions in the size of Te inclusions possible

Detector A – Traveling Heater Method

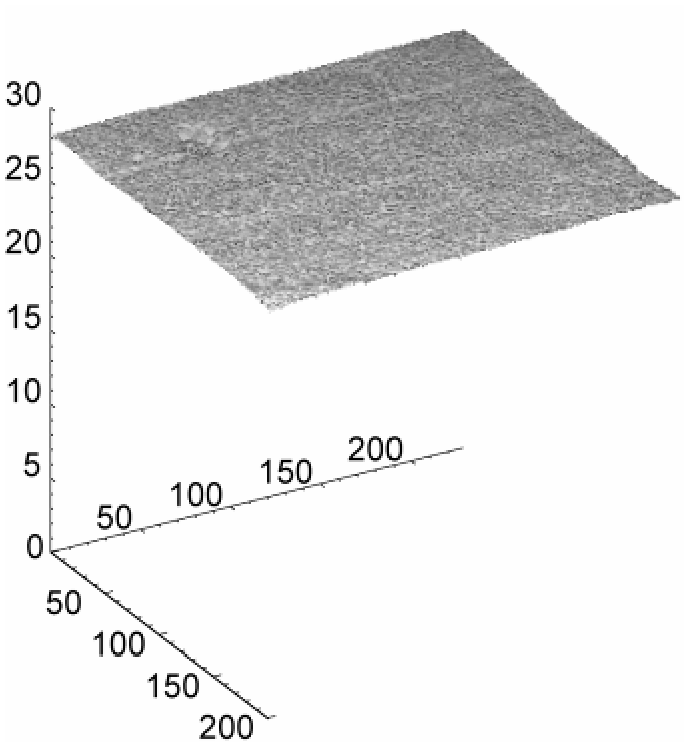
Detector B – Bridgman Method



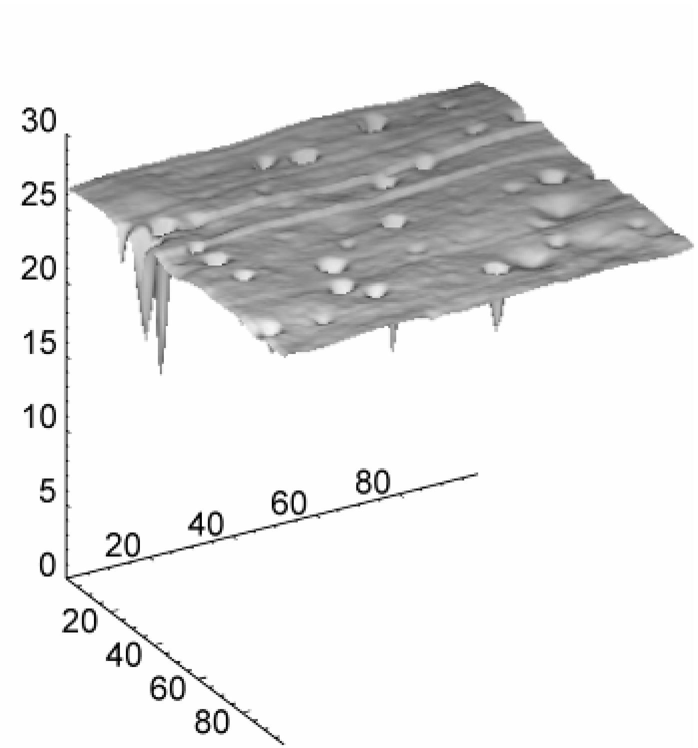
(FOV = 3.9mmx5.3mm, same magnification)

High-resolution X-ray response maps for different growth techniques

Mapping of CZT materials from two growth processes



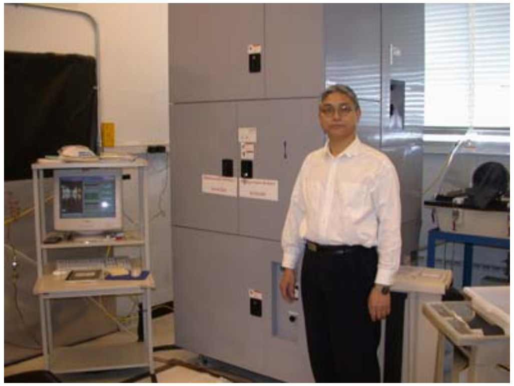
THM



Bridgman

Floating zone method also works!

Using a floating zone method, we produced CZT with no inclusions with sizes > 2 μm, good mu-tau product, 3×10^{-3} cm^2/V, and resistivity > 10^{10} Ohm-cm. Full compensation at 0.1 ppm indium dopant.



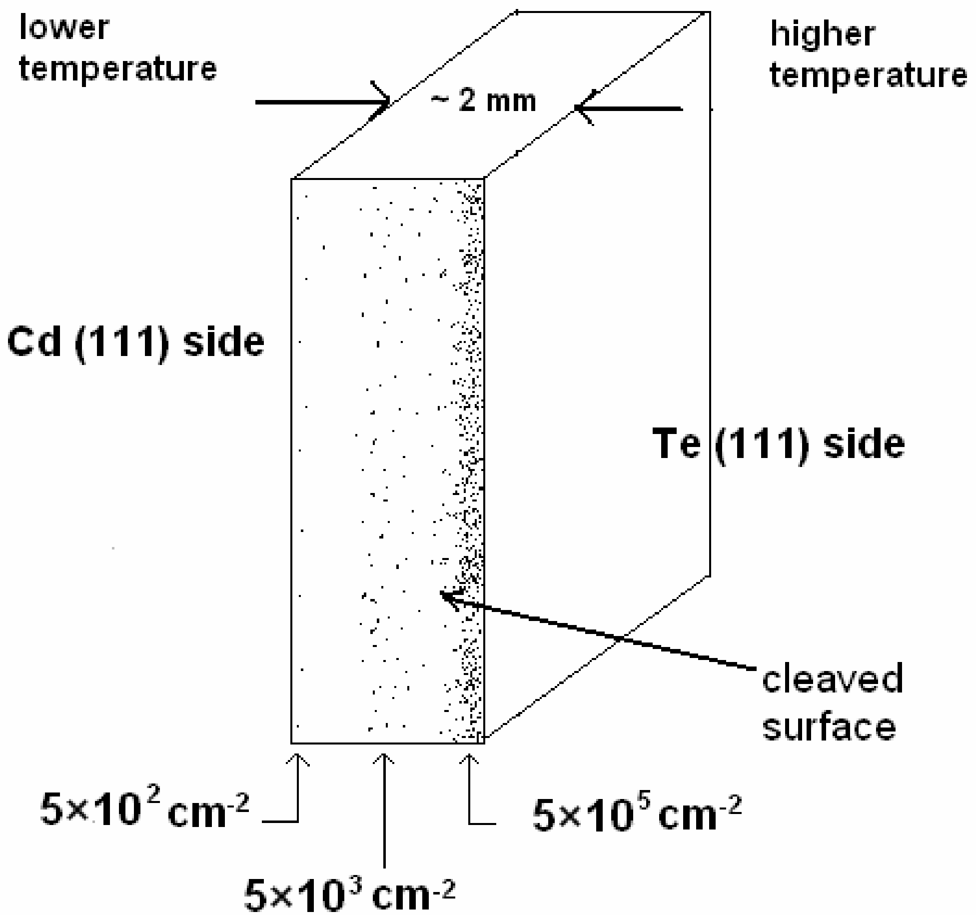
Ingot dimensions: 20-mm diameter and 300-mm length

IR transmission

Post-growth thermal annealing also holds promise

Annealing in a gradient temperature found to reduce the Te inclusions and precipitates.

The sample after 4-day annealing in Cd vapour and in a temperature gradient of 10 K/cm



Conclusions

• Project results have simulated many new ideas on characterization of Te inclusions/precipitates, different growth methods, and post-growth annealing experiments

• Use of CZT detectors is limited by the availability of *uniform*, large-volume CZT crystals.

• The first-order problem is the presence of grain boundaries and twins. Much progress has occurred.

• The primary problem for single-crystal CZT is Te inclusions causing large fluctuations in the electron trapping.

• With improvements in material uniformity, CZT can potentially replace traditional materials used for detection of gamma radiation in many nonproliferation applications.

• Without improvements in the CZT crystal growth process, a stable supply of *large-volume* spectrometers is unlikely.

Future Directions

- Use unique mapping tools to help national labs, industry, and academic researchers
- What is the nature and origin of the secondary phases (inclusions vs. precipitates)?
- How can we eliminate the large inclusions during growth (rotation, magnetic stirring, inverted growth, etc.)?
- What is the most effective post-growth thermal annealing process?
- Do inclusions getter impurities?
- What are the residual defects after annealing?
- What is the role of charging of inclusions and surfaces on the internal E field and charge-collection efficiency?

33 Peer-Reviewed Publications

- G. A. Carini, A. E. Bolotnikov, G. S. Camarda, G. W. Wright, L. Li and R. B. James, “Effect of Te Precipitates on the Performance of CdZnTe Detectors”, Appl. Phys. Lett. 88, 143515 (2006).
- Y. Cui, M. Groza, G. W. Wright, U. N. Roy, A. Burger, L. Li, F. Lu, and R. B. James, “Characterization of Cadmium Zinc Telluride Crystals Grown from Modified Vertical Bridgman Technique”, J. of Electronic Materials, Vol. 35, No. 6, 1267-1274 (2006).
- G. A. Carini, C. Arnone, A. E. Bolotnikov, G. S. Camarda, R. De Wames, J. H. Dinan, J. K. Markunas, B. Raghothamachar, S. Sivananthan, R. Smith, J. Zhao, Z. Zhong, and R. B. James, “Material Quality Characterization of CdZnTe Substrates for HgCdTe Epitaxy”, J. of Electronic Materials, Vol. 35, No. 6, 1495 (2006).
- G. S. Camarda, A. E. Bolotnikov, G. A. Carini, R. B. James and L. Li, “Effects of Tellurium Precipitates on Charge Collection in CZT Nuclear Radiation Detectors”, NATO Conference on Countering Nuclear and Radiological Terrorism, Chapter IV, edited by S. Apikyan and D. Diamond (Springer, The Netherlands, 2006), pp. 199-207.
- Y. C. Chang, R. B. James and J. W. Davenport, “Symmetrized-Basis LASTO Calculations on Defects in CdTe and ZnTe”, Phys. Rev. B73, 035211 (2006).
- A. E. Bolotnikov, G. S. Camarda, Y. Cui, K. T. Kohman, L. Li, M. B. Salomon, and R. B. James, “Performance-Limiting Defects in CdZnTe Detectors”, edited by Bernard Phlips, IEEE 2006 Nuclear Science Symposium, Medical Imaging Conference, Room-Temperature Semiconductor Detector Workshop, R05-2 (2006).
- H. Chen, S. A. Awadalla, R. Redden, G. Bindley, A. E. Bolotnikov, G. S. Camarda, G. Carini, and R. B. James, “High-Performance, Large-Volume THM CdZnTe Detectors for Medical Imaging and Homeland Security Applications”, edited by Bernard Phlips, IEEE 2006 Nuclear Science Symposium, Medical Imaging Conference, Room-Temperature Semiconductor Detector Workshop, R05-3 (2006).
- A. E. Bolotnikov, G. S. Camarda, G. A. Carini, Y. Cui, L. Li and R. B. James, “Cumulative Effects of Te Precipitates in CdZnTe Radiation Detectors”, Nucl. Instruments and Methods A571, 687-698 (2007).

33 Peer-Reviewed Publications (continued)

- G. A Carini, A. E. Bolotnikov, G. C. Camarda, G. W. Wright and R. B. James, “Non-uniformity Effects in CdZnTe Coplanar-Grid Detectors”, Physica Status Solidi (b), vol. 244, No. 5, pp. 1589-1601 (2007).
- G. A. Carini, A. E. Bolotnikov, G. S. Camarda, and R. B. James, “High-resolution X-ray Mapping of CdZnTe Detectors”, Nucl. Instruments and Methods A579, 120-124 (2007).
- A. E. Bolotnikov, G. S. Camarda, G. A. Carini, Y. Cui, L. Li and R. B. James, “Modeling the Effects of Te Precipitates on Electron Transport in CdZnTe Detectors”, Nucl. Instruments and Methods A 579, 125-129 (2007).
- G. S. Camarda, A. E. Bolotnikov, Y. Cui, K. T. Kohman, and R. B. James, “CdZnTe room-temperature semiconductor gamma-ray detector for national-security applications”, IEEE Systems, Applications and Technology Conference, ISBN: 978-1-4244-1302-7, IEEE Xplore, Digital Object Identifier: 10.1109/LISAT.2007.4312640, pp. 1-8 (2007).
- Y. Cui, M. Groza, U. N. Roy, A. Burger, and R. B. James, “Study of the Variation of Electron Mobility-Lifetime Product and Surface Recombination of $Cd_{1-x}Zn_xTe$ Radiation Detectors Using Direct Current Photoconductivity”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VIII, Vol. 6319, edited by L. A. Franks, A. Burger, R. B. James, H. B. Barber, F. P. Doty, and H. Roehrig (SPIE, Bellingham, WA, 2006), 63190C-1.
- G. A. Carini, A. E. Bolotnikov, G. S. Camarda, Y. Cui, H. Jackson, A. Burger, K. T. Kohman, L. Li and R. B. James, “Te Inclusions and their Relationship to the Performance of CdZnTe Detectors”, Invited Paper, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VIII, Vol. 6319, edited by L. A. Franks, A. Burger, and R. B. James (SPIE, Bellingham, WA, 2006), 631906-1.
- G. S. Camarda, A. E. Bolotnikov, G. A. Carini, Y. Cui, K. T. Kohman, L. Li and R. B. James, “High Spatial-Resolution Imaging of Te Inclusions in CZT Material”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VIII, Vol. 6319, edited by L. A. Franks, A. Burger, and R. B. James (SPIE, Bellingham, WA, 2006), 63190Z-1.

33 Peer-Reviewed Publications (continued)

- M. Chu, S. Terterian, G. A. Carini, G. S. Camarda, A. E. Bolotnikov, R. B. James, D. Xu, and Z. He, “Effects of Material Improvement on CZT Detectors”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VIII, Vol. 6319, edited by L. A. Franks, A. Burger, and R. B. James (SPIE, Bellingham, WA, 2006), 631905-1.
- A. E. Bolotnikov, M. Black, G. S. Camarda, G. A. Carini, Y. Cui, K. T. Kohman, L. Li, M. Salomon and R. B. James, “The Effect of Te Precipitates on Characteristics of CdZnTe Detectors”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VIII, Vol. 6319, edited by L. A. Franks, A. Burger, and R. B. James (SPIE, Bellingham, WA, 2006), 631903-1.
- H. Chen, S. A. Awadalla, K. Iniewski, P. H. Lu, F. Harris, J. MacKenzie, T. Hasanen, W. Chen, R. Redden, G. Bindley, I. Kuvvetli, C. Budtz-Jorgensen, P. Luke, M. Amman, J. S. Lee, A. E. Bolotnikov, G. S. Camarda, Y. Cui, A. Hossain, and R. B. James, “Large-Volume, High-Resolution Cadmium Zinc Telluride Radiation Detectors: Recent Developments”, Invited Paper, SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics IX, edited by R. B. James, A. Burger and L. A. Franks (SPIE, Bellingham, WA, 2007), 670602.
- A. E. Bolotnikov, G. S. Camarda, G. A. Carini, Y. Cui, L. Li and R. B. James, “Modeling the Geometrical Effects of Te Precipitates on Electron Transport in CdZnTe”, Nucl. Instruments and Methods A, accepted 1/14/07.
- K. C. Mandal, S. H. Kang, M. Choi, A. Kargar, M. J. Harrison, D. S. McGregor, A. E. Bolotnikov, G. A. Carini, G. C. Camarda, and R. B. James, “Characterization of Low-Defect Cd0.9Zn0.1Te and CdTe Crystals for High-Performance Frisch Collar Detectors”, IEEE Trans. on Nuclear Science 54, No. 4, 802 (2007).
- V. Babentsov, J. Franc, H. Elhadidy, M. Fiederle, and R. B. James, “Dependence of the Sn0/2+ charge state on the Fermi-level in semi-insulating CdTe”, Journal of Materials Research, Vol. 22, No. 11, 3249-3254 (2007).

33 Peer-Reviewed Publications (continued)

- G. S. Camarda, N. M. Abdul-Jabbar, S. Babalola, A. E. Bolotnikov, Y. Cui, A. Hossain, E. Jackson, H. Jackson, J. R. James, A. L. Luryi, M. Groza, A. Burger, and R. B. James, “Characterization and Measurements of CZT Material: Novel Techniques and Results”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics IX, Vol. 6706, edited by R. B. James, A. Burger and L. A. Franks (SPIE, Bellingham, WA, 2007), 670605.
- N. N. Kolesnikov, E. B. Borisenko, D. N. Borisenko, V. V. Kveder, and R. B. James, “Recrystallization of Ceramic Material Fabricated from Cd1-xZnxTe”, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics IX, Vol. 6706, edited by R. B. James, A. Burger and L. A. Franks (SPIE, Bellingham, WA, 2007), 67061B.
- A. E. Bolotnikov, G. S. Camarda, A. Hossain, Y. Cui and R. B. James, “Effectiveness of Electrostatic Shielding and Electronic Subtraction to Correct for Hole Trapping in CdZnTe Semiconductor Detectors”, Invited Paper, in Proceedings of SPIE Conference on Optics and Photonics in Global Homeland Security III, Volume **6540**, edited by T. E. Saito, D. Lehrfeld, and M. J. DeWeert, 65401F, May 4, 2007.
- G. S. Camarda, A. E. Bolotnikov, Y. Cui, A. Hossain, and R. B. James, “Polarization Studies of CdZnTe Detectors Using Synchrotron X-ray Radiation”, submitted to IEEE NSS/MIC Conference Record, November 2007.
- A. E. Bolotnikov, G. S. Camarda, G. A. Carini, Y. Cui, K. T. Kohman, L. Li, M. B. Salomon, and R. B. James, “Performance-Limiting Defects in CdZnTe Detectors”, IEEE Transactions on Nuclear Science, Vol. 54, No. 4, pp. 821-827 (2007).
- H. Chen, S. A. Awadalla, K. Iniewski, P. H. Lu, F. Harris, J. Mackenzie, T. Hasanen, W. Chen, R. Redden, G. Bindley, I. Kuvetli, C. Budtz-Jorgensen, P. Luke, M. Amman, J. S. Lee, A. E. Bolotnikov, G. S. Camarda, Y. Cui, A. Hossain and R. B. James, “Characterization of Large Cadmium Zinc Telluride Crystals Grown by Traveling Heater Method”, J. of Appl. Phys. 103, Issue 1, 014903 (2008),

33 Peer-Reviewed Publications (continued)

- A. Hossain, A. E. Bolotnikov, G. S. Camarda, Y. Cui, S. Babalola, A. Burger, and R. B. James, “Effects of Surface Processing on the Response of CZT Gamma Detectors: Studies with a Collimated Synchrotron X-Ray Beam”, J. of Electronic Materials, DOI: 10.1007/s11664-008-0431-6, 2008.
- V. Babentsov, J. Franc, A. Fauler, M. Fiederle and R. B. James, “Doping, Compensation, and Photosensitivity of Detector-Grade CdTe”, Journal of Materials Research, accepted for June 2008 publication.
- V. Babentsov, J. Franc, A. Fauler, M. Fiederle and R. B. James, “Distribution of Zinc, Resistivity and Photosensitivity in a Vertical Bridgman Grown Cd1-xZnxTe Ingot”, J. of Crystal Growth, submitted 3/6/08.
- A. E. Bolotnikov, G. S. Camarda, Y. Cui, A. Hossain, G. Yang, W. Yao, and R. B. James, “Internal Electric-Field Lines Distribution in CdZnTe Detectors Measured Using an X-ray Mapping Technique”, submitted to Nucl. Instr. And Methods, 6/2008.
- A. Hossain, A. E. Bolotnikov, G. C. Camarda, Y. Cui, G. Yang, and R. B. James, “Defects in Cadmium Zinc Telluride Crystals revealed by etch pit distributions”, J. Crystal Growth, submitted 6/2008.
- A. E. Bolotnikov, G. S. Camarda, Y. Cui, A. Hossain, G. Yang, W. Yao and R. B. James, “Internal electric-field distribution in CdZnTe detectors measured using X-ray mapping”, IEEE Trans. on Nuclear Science, submitted 6/2008.

35 Presentations, 2 IEEE National Awards and 1 Patent

- "Advanced Nuclear Detectors to Interdict Smuggling Events", NATO Workshop on Countering Nuclear and Radiological Terrorism, Yerevan, Armenia, October 3-7, 2005.
- "Non-Uniform Response of CdZnTe Material for Planar, Co-Planar Grid and Pixel Detectors", IEEE Nuclear Science Symposium, San Juan, Puerto Rico, Oct. 24-27, 2005.
- "Long Drift-Length Cadmium Zinc Telluride Gamma-Ray Detectors", 2006 Symposium on Radiation Measurements and Applications, Ann Arbor, MI, May 23-26, 2006.
- "Modeling the Geometrical Effect of Te Precipitates on Charge Transport in CdZnTe Detectors", 2006 Symposium on Radiation Measurements and Applications, Ann Arbor, MI, May 23-26, 2006.
- "The Effects of Te Precipitates on Measurable Characteristics of CdZnTe", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 14, 2006.
- "CZT: Recent Progress and Issues", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 14, 2006.
- "Effects of Te Precipitates on the Uniformity of CdZnTe", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 14, 2006.
- "Study of the Variation of Electron Mobility-Lifetime Product and Surface Recombination Velocity of $Cd_{1-x}Zn_xTe$ Radiation Detectors Using Direct Current Photoconductivity", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 14, 2006.
- "Deviations of CZT Detector Response Caused by Isolated Te Precipitates", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 15, 2006.
- "CdTe and $Cd_{(0.9)}Zn_{(0.1)}Te$ Crystal Growth and Characterization for Nuclear Spectrometers", SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics VIII, San Diego, CA, August 15, 2006.

35 Presentations, 2 IEEE National Awards and 1 Patent

National Nuclear Security Administration

- “Material Properties Limiting the Use of Cadmium Zinc Telluride X- and Gamma Detectors”, Conference on Wide Band-gap II-VI Semiconductors: Growth, Characterization and Applications, European Materials Research Society Meeting, Warsaw, Poland, September 5, 2006.
- “Material Requirements in the Group – CdTe, CdZnTe, and CdMnTe – and recent advances for X-ray and Gamma-Ray Applications”, Conference on Wide Band-gap II-VI Semiconductors: Growth, Characterization and Applications, European Materials Research Society Meeting, Warsaw, Poland, September 5, 2006.
- “Micro-Characterization of CdZnTe Detectors”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, October 30, 2006.
- “Characterization of Low Defect $Cd_{0.9}Zn_{0.1}Te$ and CdTe Crystals for High Performance Frisch Collar Detectors”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, October 30, 2006.
- “Performance-Limiting Defects in CdZnTe Detectors”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, October 31, 2006.
- “High-Performance, Large-Volume THM CdZnTe Detectors for Medical Imaging and Homeland Security Applications”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, October 31, 2006.
- “Quantitative Measurements of Micro-Defects in CdZnTe”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, November 1, 2006.
- “Te Precipitates in CdZnTe (Zn=10%) Radiation-Detection Materials”, 15th International Room-Temperature Semiconductor Detector Workshop, San Diego, CA, November 1, 2006.
- “Effectiveness of electrostatic shielding and electronic subtraction to correct for the hole trapping in CdZnTe semiconductor detectors”, Invited Talk, SPIE Defense and Security Symposium, Orlando, FL, April 12, 2007.

35 Presentations, 2 IEEE National Awards and 1 Patent

- “Brookhaven National Laboratory Energy and Homeland-Security Initiatives”, Key-note address, IEEE Systems, Applications, and Technology Conference, Farmingdale State University, Farmingdale, NY, May 4, 2007.
- “Correcting the Non-Uniformity in the Gamma-Ray Response of CZT Detectors”, Presentation at the NA22 SNM Movement Detection, Radiation Sensors, and Advanced Materials Program Review Meeting, Lawrence Livermore National Lab, Livermore, CA, July 19, 2007.
- “Cadmium Zinc Telluride X- and Gamma-Ray Detectors”, Presentation to GE Global Research Lab, Albany, NY, July 31, 2007.
- “Recent Developments of Large-Volume Cadmium Zinc Telluride High-Resolution Radiation Detectors”, SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics IX, August 27, 2007, San Diego, CA.
- “Defect Studies and Electric-Field Distribution in CdZnTe Detectors”, SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics IX, August 27, 2007, San Diego, CA.
- “Recrystallization in Ceramic Material Fabricated from Cadmium Zinc Telluride Nanopowders”, SPIE Conference on Hard X-Ray and Gamma-Ray Detector Physics IX, August 29, 2007, San Diego, CA.
- “Material Properties Degrading the Performance of CZT Radiation Detectors”, 13th International Conference on II-VI Compounds, September 11, 2007, Jeju, South Korea.
- “Room-Temperature Semiconductor Radiation Detectors”, University of Connecticut, October 12, 2007, Storrs, CT.
- “Studies of the Effects of Te Inclusions in CdZnTe Radiation Detectors”, IEEE Nuclear Science Symposium, October 31, 2007, Honolulu, HA.

35 Presentations, 2 IEEE National Awards and 1 Patent

- “Polarization Studies of CdZnTe Detectors Using Synchrotron X-Ray Radiation”, IEEE Nuclear Science Symposium, October 31, 2007, Honolulu, HA.
- “CZT Gamma-Ray Detectors”, University of Michigan Colloquium, April 4, 2008, Ann Arbor, MI.
- “Room-Temperature Semiconductor Gamma Detectors”, University of Freiburg Seminar, April 14, 2008, Freiburg, Germany.
- “The Effect of Te Inclusions in Cadmium Zinc Telluride Radiation Detectors”, NA22 Workshop on CZT Detectors, April 23, 2008, Washington State University, Pullman, WA.
- “Investigation of the Non-Uniformity in the Gamma-Ray Response of CdZnTe”, National Synchrotron Light Source Annual Users’ Meeting, May 19, 2008, BNL, Upton, NY.
- “Effects of Extended Defects in CZT Using a Synchrotron X-Ray Beam”, Symposium on Radiation Measurements and Applications, June 2, 2008, University of California, Berkeley, CA.
- “Internal Electric-Field Distribution in CdZnTe Detectors Measured Using X-Ray Mapping”, Symposium on Radiation Measurements and Applications, June 3, 2008, University of California, Berkeley, CA.

National Awards:

(1) 2006 IEEE Radiation Instrumentation Outstanding Achievement Award

(2) 2007 IEEE Harold Wheeler Award

Patent Application: ”A High-Energy Detector”, Inventors: A. E. Bolotnikov, G. Camarda, Y. Cui and R. B. James, submitted March 27, 2008.

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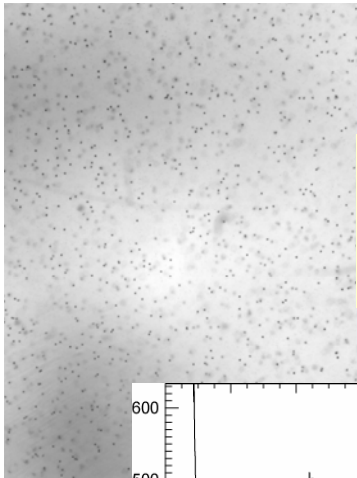
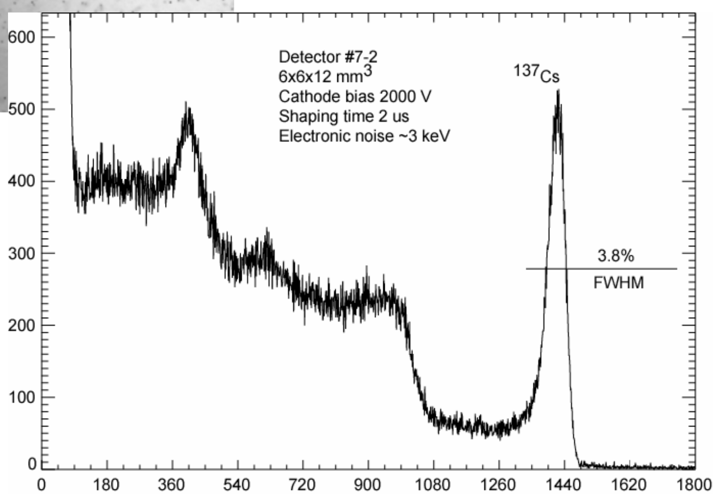
Thank You!

Energy resolutions of <0.8% achievable for long-drift detectors

Responses of two detectors fabricated from different growth runs

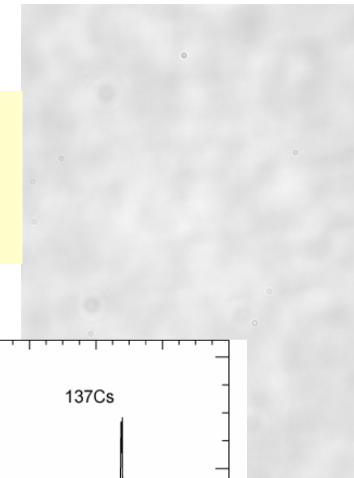


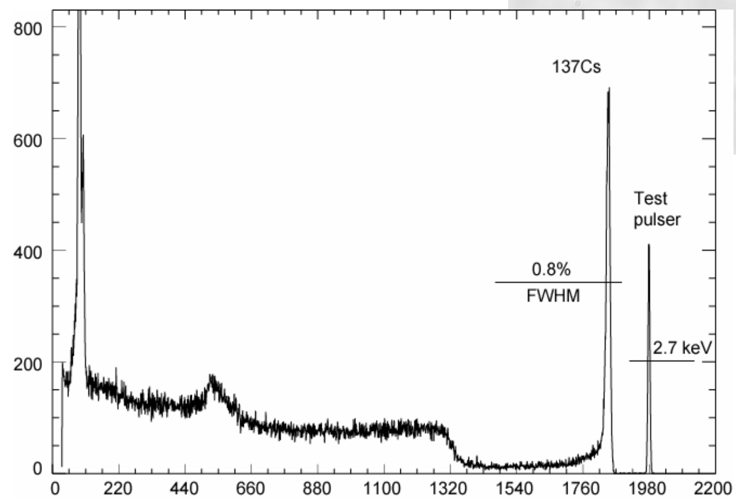
High concentration of 3-20-micron inclusions, ~10^5 cm^{-3}.



Energy resolution of 3.8% at 662 keV
6x6x12 mm^3

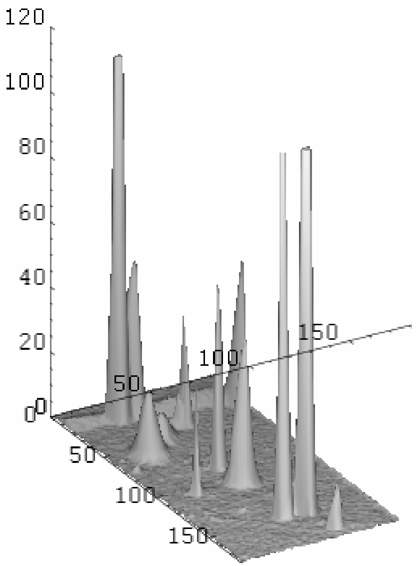
High concentration of 1-2-micron inclusions, ~10^6 cm^{-3}





Energy resolution of 0.75% at 662 keV
4.5x4.5x11 mm^3

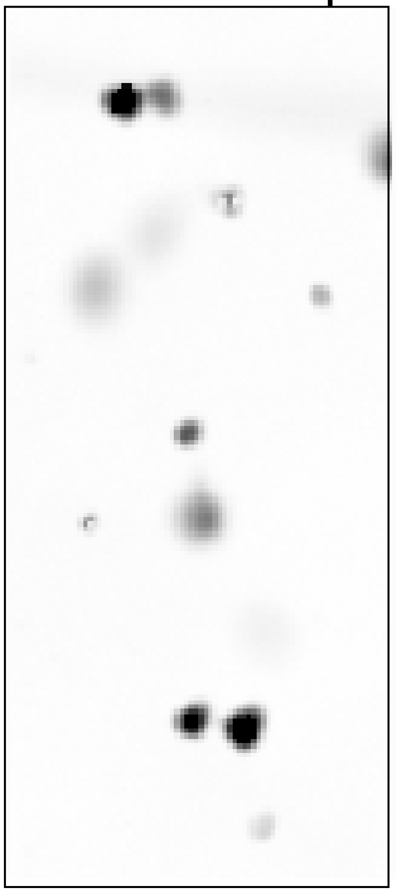
Correlation between electron and hole collection maps observed



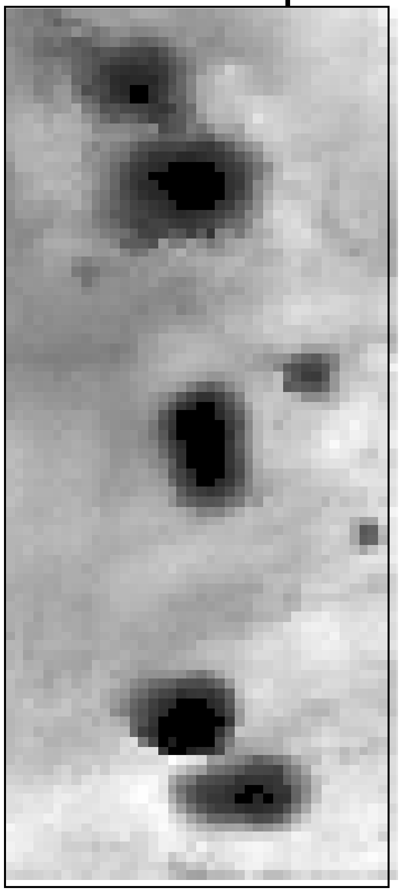
1.5-mm thick

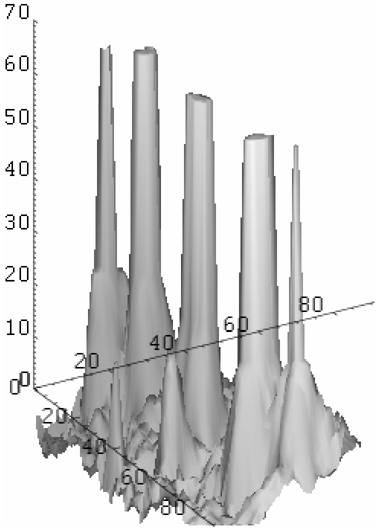
CZT sample

Electron Map



Hole Map





20 keV X rays; Cathode bias 280 V;
Resolution 10 mm; 91x41 pixels